FLOOD FORECAST UNCERTAINTY AND ALERT DECISION. APPLICATION TO THE ALPINE RHONE RIVER CATCHMENT

Incertitude des prévisions de crue et décision d'alerte. Application au bassin du Rhône Alpin

Javier García Hernández, Jean-Louis Boillat, Anton J. Schleiss

Laboratoire de Constructions Hydrauliques (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland
javier.garciahernandez@epfl.ch, jean-louis.boillat@epfl.ch, anton.schleiss@epfl.ch
Phone : +41 (0) 21 693 23 85 ; Fax : +41 (0) 21 693 22 64

KEY WORDS

Deterministic and ensemble forecast, hydrological modeling, flood simulation, warning report

ABSTRACT

The main goal of the 3rd Rhône Correction project in Switzerland is to improve the flood protection in the Upper Rhone River basin. In this framework, the MINERVE project contributes to the flow control during flood events by preventive turbine and bottom outlet operations from the numerous storage power plants existing in the watershed.
For this purpose, a semi-distributed hydrological model was developed for the Upper Rhone River basin. It is currently operational for a real-time flood forecast in the Rhone Valley. It simulates the snow and glacier melt, soil infiltration and run-off processes, flood routing in rivers and reservoirs as well as hydropower scheme operations.
For the computation of flood prediction, the numerical meteorological forecast models COSMO-2, COSMO-7 and the probabilistic COSMO-LEPS, delivered by MeteoSwiss, have been assimilated. The forecasts were used as input for the hydrological simulation of three historical flood periods and the results are analyzed and discussed.
Furthermore, a warning report providing flood warnings has been also developed. It gives the evolution of the hydrological situation at control points in the catchment area. Finally, it provides three levels warnings during a flood situation depending on respective critical discharge thresholds.

RESUME

L'objectif principal du projet suisse de la Troisième Correction du Rhône est l'amélioration de la protection contre les crues sur le bassin alpin du Rhône à l'amont du Léman. Dans ce contexte, le projet MINERVE contribue au contrôle des débits pendant les crues grâce à des opérations préventives de turbinage et de vidange aux aménagements hydroélectriques existants sur le bassin versant.
Pour ce faire, un modèle hydrologique semi-distribué a été développé au Rhône Alpin. Il est actuellement opérationnel pour la prévision de crue en temps réel, en simulant la fonte de neige et de glace, l'infiltration au sol et les processus de ruissellement, le routage des crues dans les rivières et réservoirs ainsi que les opérations des aménagements hydroélectriques.
Pour le calcul de la prédiction des crues, les prévisions météorologiques déterministes COSMO-2, COSMO-7 et probabilistes COSMO-LEPS, fournies par MétéoSuisse, ont été assimilées. Les prévisions météorologiques ont été utilisées comme input pour les simulations hydrologiques de trois périodes de crues historiques et les résultats sont analysés et discutés.
De plus, un bulletin d'avertissement de crues a été développé. Il donne l'évolution de la situation hydrologique aux points de contrôle du bassin versant et active les trois niveaux d'avertissement pendant un épisode de crue en fonction de seuils critiques de débit prédéfinis.

1. INTRODUCTION

During the last decades, several flood events caused important inundations in the Upper Rhone River basin in Switzerland, leading to complementary projects which aim to improve the security and reduce the damages. In this framework, the MINERVE project [1, 2] contributes to a better flow control during flood events in the Rhone River basin, taking advantage from the existing multireservoir system. This project also fits into the OWARNA national warning concept aiming to establish a Swiss alarm platform for natural hazards.

The developed MINERVE system assesses the hydro-meteorological situation on the watershed and provides hydrological forecasts with a horizon from one to five days. It also helps to the evaluation of priority decisions concerning preventive actions or management of the hydropower plants for security purposes. Their influence during floods can be significant while appropriate operations are able to reduce the peak discharges in the Rhone River and its main tributaries [3], thus avoiding or limiting the damages as well.

The MINERVE system exploits flow measurements, data from reservoirs and hydropower plants as well as deterministic (COSMO-7 and COSMO-2) and ensemble (COSMO-LEPS) meteorological forecasts from MeteoSwiss.

The *Routing System* software is used for numerical computations, being capable of simulating the formation and propagation of free surface flows in complex systems. The semi-distributed hydrological model includes 239 sub-catchments divided in 1059 elevation bands in order to describe the temperature-driven processes accurately. The input data of the bands are precipitation, temperature and potential evapotranspiration.

A warning report is given for each hydrological forecast, supplying a warning level at the selected control points according to time. The assessment of the system is done regarding the percentage of hits, false alarms and misses for the different hydro-meteorological forecasts. This approach allows managing the uncertainties related to forecast and provides a support to decision.

Simulation results show a good performance regarding the warning level at the outlet of the basin, even if an uncertainty is associated to the warning results as well as for the delay of occurrence. Nevertheless, an intelligent utilization of the hydrological forecasts, taking into account past and current time observations, can offer a good evaluation of the future situation, providing appropriate decisions.

2. METEOROLOGICAL FORECASTS

MeteoSwiss delivers the meteorological forecasts produced by the « Consortium for Small-scale Modelling » (COSMO). The characteristics of the current models are presented in Table 1.

	COSMO-LEPS	COSMO-7	COSMO-2
Forecast type	Probabilistic (16 members)	Deterministic	Deterministic
Resolution	7 km	6.6 km	2.2 km
Vertical levels	40	60	60
Lead time	0-132 h	0-72 h	0-24 h
Temporal resolution	3 h	1 h	1 h
Update	24 h	12 h	3 h

Table 1 : Characteristics of the COSMO models of the Federal Office of Meteorology and Climatology, MeteoSwiss

MINERVE model uses the deterministic meteorological forecast COSMO-7, which is driven by the global model ECMWF (European Centre for Medium-Range Weather Forecasts) and covers most of western and central Europe. Deterministic COSMO-2 forecast are also used. It is driven by COSMO-7 (for the initial and boundary conditions) and covers, with a finer resolution, the Alpine region with Switzerland at the center. Both of them offer the benefit of nowcasting and short range forecasting.

Furthermore, the probabilistic forecast COSMO-LEPS (Limited-area Ensemble Prediction System) is used as well. This model supplies 16 ensembles with high resolution for central and southern Europe. Initial boundary conditions are representative members of the ECMWF ensemble. The purpose of COSMO-LEPS is the improvement of the early and medium-range predictability of extreme and localized weather events, particularly when orographic and mesoscale-related processes play a crucial role [4].

3. HYDROLOGICAL MODEL

The concept of the hydrological model used to simulate the discharge at the outlet of each sub-catchment [5] is based on the SOCONT [6] and GSM-Socont [7, 8] models and takes into account all hydraulic structures of the dams and hydropower plants.

The semi-distributed hydrological model includes 239 sub-catchments. If a glacier part exists, the sub-catchment is divided into glacier and non-glacier elevation bands. Otherwise, it is just divided in non-glacier elevation bands. Every band is supplied by a virtual meteorological station, which provides hourly precipitation and temperature series, and a model of snow composed of a double reservoir (snow and liquid water contained in the snow layer). It uses the hydrological simulation to follow the temporal evolution of the height and saturation degree of the snow. The snow melt is calculated according to a degree-day formula and produces an equivalent precipitation starting from a rate of saturation threshold.

In the case of a non-glacier band, this equivalent precipitation supplies the infiltration and run-off model. This one is composed of two parallel non-linear reservoirs, respectively producing the slow and fast components of the discharge at the outlet of the sub-catchment. In the case of a glacier band, the equivalent precipitation resulting from the snow melt is transferred to the outlet by a linear reservoir. When no more snow exists on the glacier band, a degree-day glacier melt model produces a discharge which is also transferred to the outlet by a linear reservoir. The total discharge of the sub-catchment is the sum of the contributions of each elevation band.

This semi-distributed hydrological model has been built using the hydrological and hydraulic simulation tool *Routing System* [9]. This software simulates the formation and the propagation of free surface flows in a complex system. It allows hydrological and hydraulic modelling by an oriented object approach, according to a semi-distributed conceptual scheme (Figure 1), and taking into account special processes such as snow and glacier melt, surface and sub-surface flows, routing in reservoirs or rivers as well as hydraulic regulation works such as valves, gates, water intakes turbines or pumps. The model can be analyzed at different information levels thanks to the aggregation facilities.

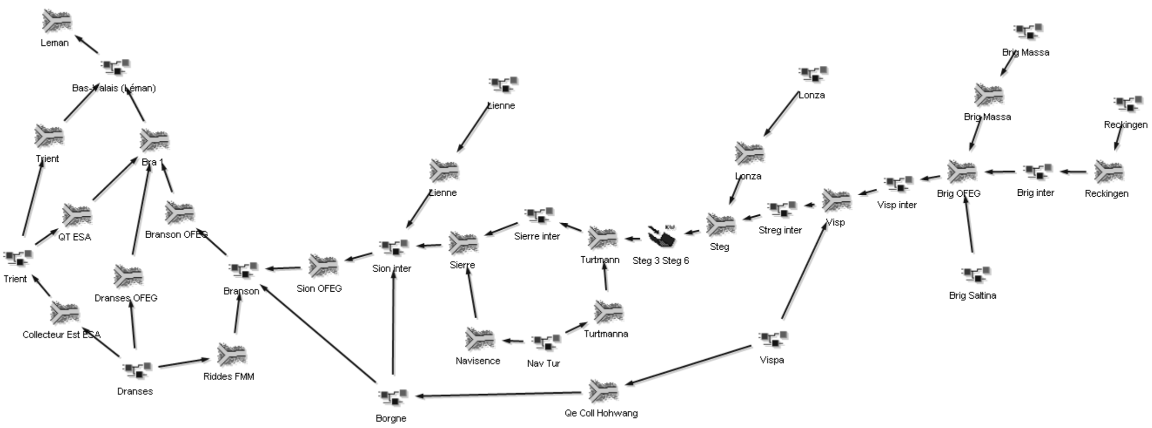

Figure 1: Semi-distributed hydrological model of the Upper Rhone River catchment, at the highest level scale

4. ANALYSIS AND RESULTS

After resimulations of several past events, hydrological simulations of three historical flood periods (Table 2) have been realized and the results analyzed. Forecasts have been divided in periods of 24 h in order to study the performance depending on the horizon time. Only the days of a forecast included on the flood period were taken into account for this work. Besides, ensemble forecast was characterized by representative hydrographs as the median (q_m), the lower (q_l) and upper quartiles (q_u) as well as by the minimal (q_{min}) and maximal discharges (q_{max}) for easily understanding the behavior of the forecast.

Start		Final	Peak flow	COSMO-7	COSMO-LEPS	COSMO-2
23.09.1993 12h	-	26.09.1993 12h	1081	✓	✓	-
14.10.2000 00h	-	18.10.2000 00h	1358	✓	✓	-
27.05.2008 12h	-	01.06.2008 12h	815	✓	✓	-

Table 2 : Last historical floods in the Upper Rhone River basin

Figure 2 shows the cumulated volume ratio (r_{CVol}) for a simulation with all the COSMO-LEPS and COSMO-7 meteorological forecasts, where r_{CVol} represents the coefficient between the simulated volumes and the observed ones. COSMO-LEPS does not provide a systematic bias for the median hydrograph q_m. It doesn't either depend on the forecast delay, but the range between the lower quartile hydrograph q_l and the upper quartile q_u increases with the horizon delay. The hydrograph q_l always provides ratios smaller than one and the hydrograph q_u higher than one. COSMO-7 provides, in general, higher values of precipitation for first thresholds (700 and 1000 m^3/s) and the quality of the forecast is degraded with the horizon time. Besides, the values given by COSMO-7 are normally higher than the hydrograph q_u of COSMO-LEPS.

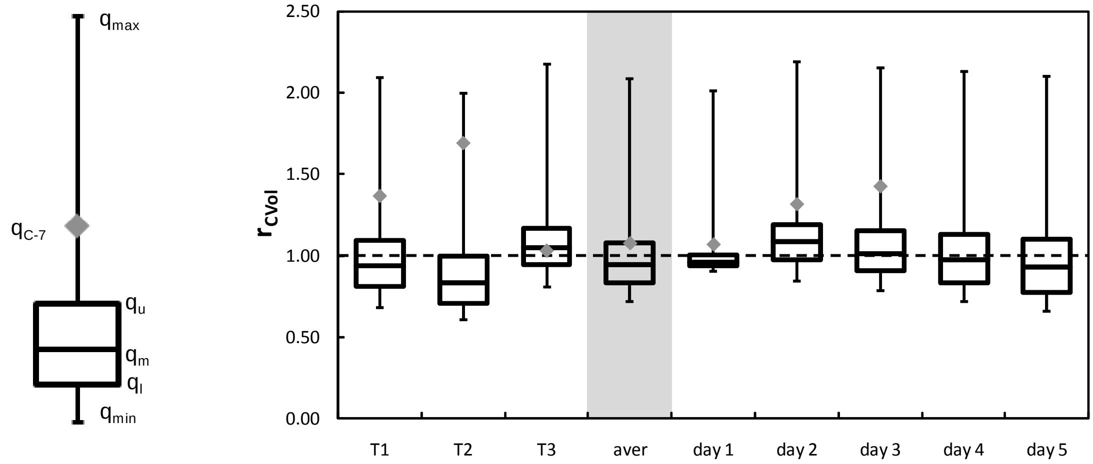

Figure 2 : Cumulated volume ratio at Porte-du-Scex (outlet of the watershed) for the simulation with COSMO-LEPS meteorological forecast (q_{max}, q_u, q_m, q_l and q_{min}) and COSMO-7 (q_{C-7}) for different thresholds (T1 for Q=700 m^3/s, T2 for Q=1000 m^3/s and T3 for Q=1200 m^3/s), for the average "aver" and for different horizon delays (day 1 to day 5, where "day 1" represents the 0-24 h period, "day 2" the 24-48 h period and so on)

The normalized peak error (NPE) against the peak time error (PTE) is also studied dividing the forecasts in one day periods. The PTE [10] defines the time difference between the simulated and the observed peak flow. The NPE measures the relative error between the simulated and the observed peak flow [11]. The results are presented in Figure 3.

The hydrograph q_m of COSMO-LEPS provides forecasts with a peak time error between -7 and +12 h and a normalized peak error between -49% and +37% compared to the observed peak. COSMO-7 provides forecasts with a PTE between -18 and +12 h and a NPE between -32% and +63% in comparison with the observed peak. The range variability is in both cases larger for the COSMO-7 forecast. The hydrographs q_l and q_u of the ensemble increase the range of PTE between -8 and +18 h as well as the NPE between -57% and +53% compared to the observed peak, still with a performance similar to COSMO-7.

It is worth mentioning that the hydrograph q_m of COSMO-LEPS doesn't provide any forecast overestimating the peak flow in advance (left-up quadrant). It is also noteworthy that COSMO-7 either supplies forecasts smaller than the peak flow and after it (right-down quadrant). If it is used for preventive operations, the COSMO-7 option is worst because it can produce too much emptying of hydropower plants reservoirs and consequently useless energy losses.

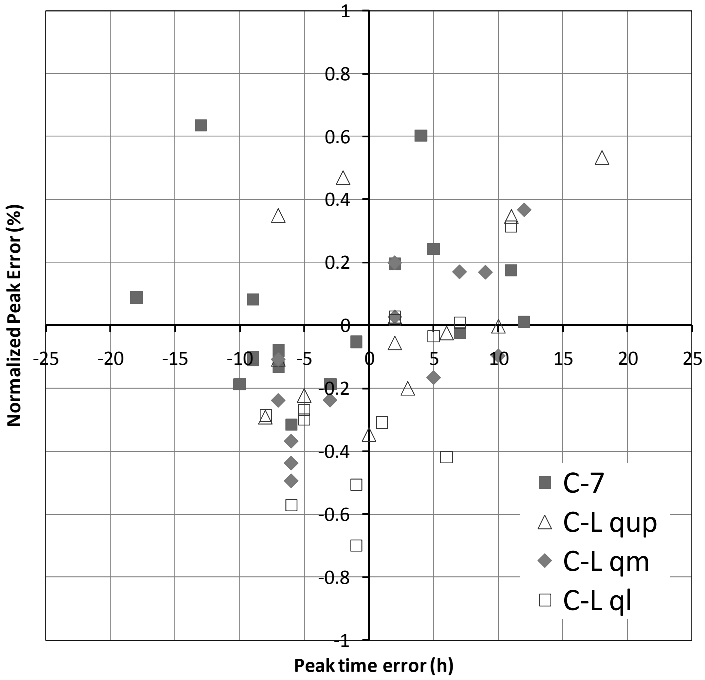

Figure 3 : Normalized Peak Error against Peak time error diagram for all the forecasts at Porte du Scex

As an example, the event of October 2000 was predicted rather well by COSMO-LEPS during the last three days before the peak flow, with a large variability on the discharge (Figure 4) depending on the representative hydrograph and with the best results for the upper quartile q_u. COSMO-7 is more unstable, predicting the peak in advance for the first forecasts analyzed, three days before the peak flow. Then, the prediction is belated for the next forecasts, two days before the peak flow (Figure 4). An overestimation of the peak flow was finally obtained one day before it.

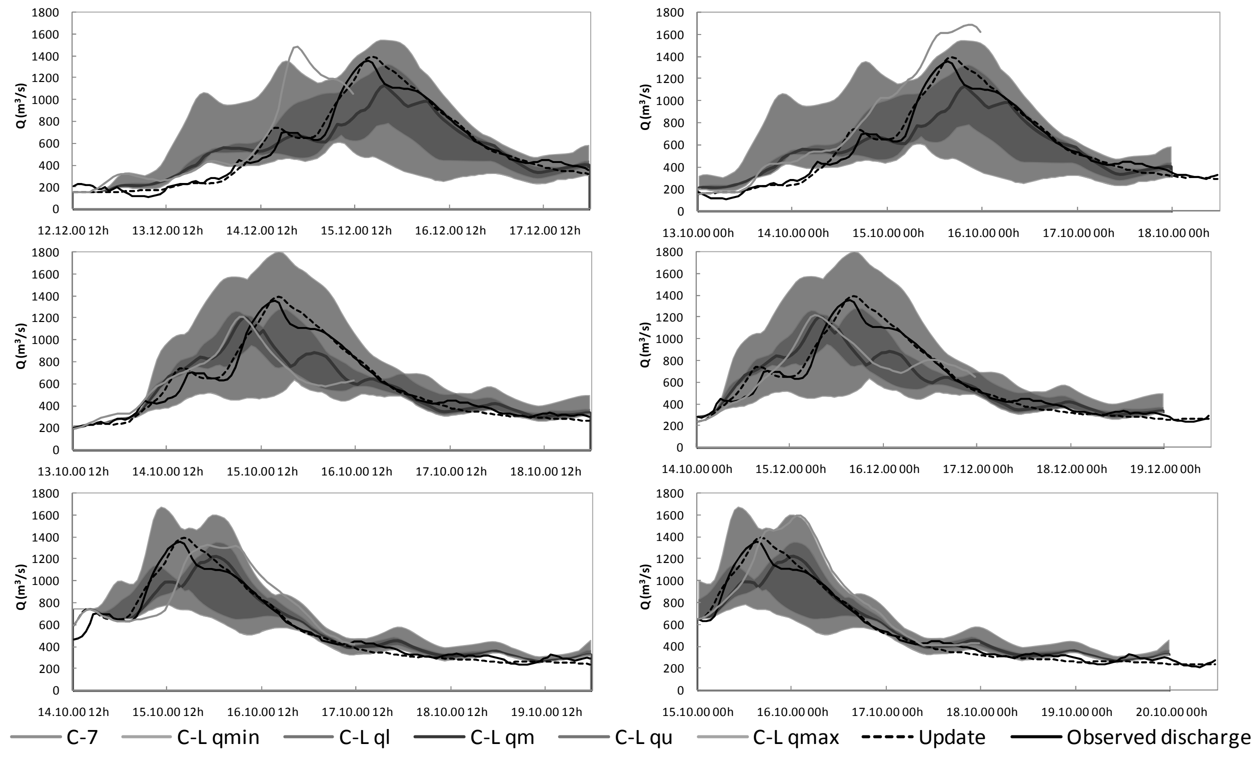

Figure 4 : Hydrological forecasts at Porte-du-Scex (outlet of the watershed) for the forecasts COSMO-LEPS (C-L) of 12, 13 and 14.10.2000 at 12h00 and for the forecasts COSMO-7 (C-7) of 12, 13 and 14.10.2000 à 12h00 and of 13, 14 and 15.10.2000 at 00h00. Simulation with observed meteorological data (Update) and comparison with the observed discharge

The results of the index Correct Alarm Ratio (CAR) and Miss Rate (MR) [12], obtained for the hydrographs q_m and q_u of the probabilistic forecast and for the deterministic one, taking also into account one day periods, are presented in Figure 5. Pie charts show that the hydrograph q_m of COSMO-LEPS is more conservative than COSMO-7 forecast, getting less false alarms but more missed events at every threshold. Comparing the probabilistic upper quartile q_u with the deterministic forecast, the number of missed events and false alarm is similar but more hits are obtained for q_u.

Observations (Event occurrence)

Forecasts		Yes	No
	yes	HIT	False Alarm
	no	Miss	Correct Rejection

$$CAR = \frac{HIT}{HIT + False\,alarm}$$

$$MR = \frac{Miss}{Miss + Correct\,rejection}$$

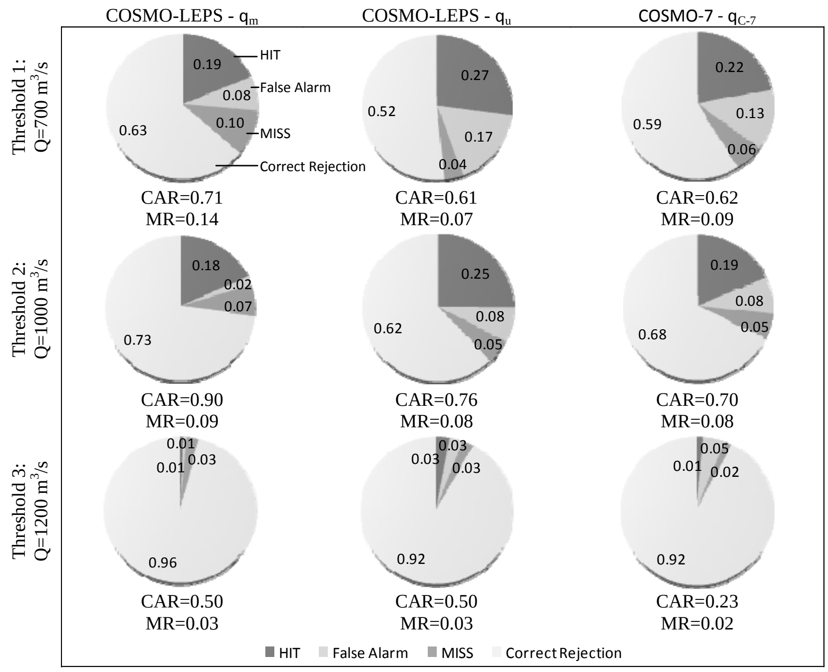

Figure 5 : Correct Alarm Ratio and Miss Rate at Porte-de-Scex for the representative hydrographs q_m and q_u of COSMO-LEPS and for COSMO-7 at different thresholds (T1 for Q=700 m^3/s, T2 for Q=1000 m^3/s and T3 for Q=1200 m^3/s)

5. WARNING REPORT

Finally, a report [13] providing flood warnings has been developed (Figure 6). It gives a prediction of the risk situation at control points along the catchment area. It gives a three levels warning report during flood situations (notice, alert and alarm) depending on critical discharge thresholds [14] and on the occurrence probability when the probabilistic forecast is considered.

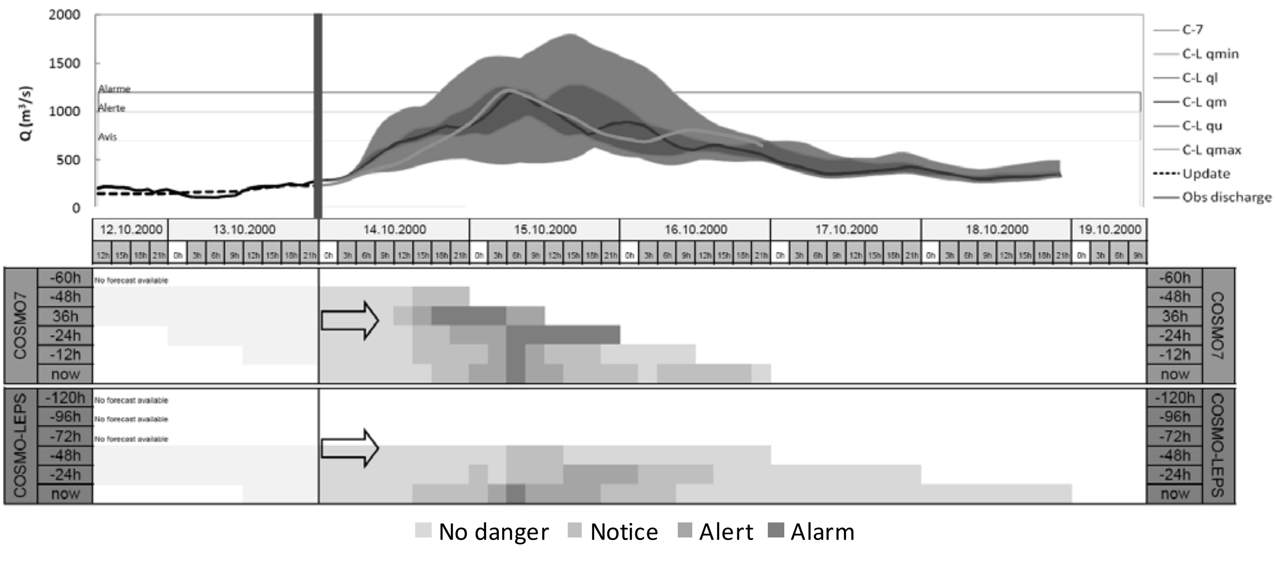

Figure 6 : MINERVE Warning Report at Porte du Scex (outlet of the watershed) on 13.10.2000 at 12h with all the available forecasts

6. CONCLUSIONS

The MINERVE model developed for the Upper Rhone River is operational with deterministic forecasts since 2006 and with ensemble forecasts since 2008 [15]. The discharge in the river network of the Upper Rhone catchment area is simulated by considering all hydraulic structures of the hydropower plants and dams as well as preventive turbine and water release operations. The flood forecast system is the basis for the decision-making tool used by a crisis task force for limiting flood damages during flood events.

COSMO-LEPS has been implemented in the project for improving the uncertainty in the meteorology. COSMO-7 and COSMO-2 are complementary for the short range forecast. The use of all available forecasts seems a good way to improve the quality of the weather prediction. Similar results from both of them with a small range of variation will help to found the decision. Nevertheless, since the hydro-meteorological task is not an exact science, the point of view of the meteorologist and the engineer is necessary for interpreting the results and the expert opinion still remains an important support of the system.

The studied historical events show the added value of a forecast system for providing warnings in case of flood. They don’t have a perfect performance but they supply an advantageous estimation of the flood and a good skill in warnings. For example, hydrographs q_m (median) and q_u (upper quartile) of the ensemble forecast, according to the Correct Alarm Ratio, are right in more than 75% of cases when a warning is given for the threshold Q=1000 m^3/s. Besides, missed alarms, according to the Miss Rate, are less than 10%. When considering the three forecasts and being able to take profit of this large information, the system can be used for providing a quality warning. In the same way, the system is also profitable for the hydropower plants management, when having the correct initial levels in the lakes and initial conditions in the basin, saturation and initial discharges among others.

The real value of a forecast remains nowadays unachievable because of the limited number of flood events available in the archive. There is no other option than to evaluate the skill of the flood forecasts on a case by case basis, not for giving a final performance of the hydro-meteorological forecasts, but for understanding the behavior and being capable to deal with it in a future situation.

The aim of simulating hydrological forecasts is to communicate the computed values as well as the uncertainty to end users. It is evident that the performance will not be the same in the future and that the full uncertainty is not represented by the model. Nevertheless, hydrological forecasts are currently considered as a good tool for making decisions. The assessment of past events is necessary for understanding new forecasts, increasing the knowledge of the meteorologists and engineers, for having a good flood management system.

ACKNOWLEDGEMENTS

The MINERVE project is developed in partnership by the Swiss Federal Office for Environment (FOEV), Roads and Water courses Service, Energy and Water Power Service of the Wallis Canton and Water, Land and Sanitation Service of the Vaud Canton. The Swiss Weather Services (MeteoSwiss) provides the weather forecasts and hydroelectric companies communicate information regarding their hydropower plants. HydroCosmos and Epicard engineering firms contribute to the computer aspects. Scientific developments are entrusted to two entities of the Ecole Polytechnique Federal Lausanne (EPFL), the Hydraulic Constructions Laboratory (LCH) and the Ecohydrology Laboratory (ECHO), as well as to the Institute of geomatics and analysis of risk (IGAR) of the University of Lausanne (UNIL).

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